

# **MULTICYCLE INTEGRATION FOCAL PLANE ARRAY (MIFPA) FOR LOCK-IN (LI-), GATED (G-), AND GATED LOCK-IN (GLI-) IMAGING, SPECTROSCOPY AND SPECTROSCOPIC IMAGING**

## **BACKGROUND OF THE INVENTION**

### **1. Field of the Invention**

This invention relates to the theory, design, fabrication, performance, and methods of its applications of a new electronic device — a new type of staring focal plane array (FPA), which utilizes the method of multicycle integration (MI) to acquire the signal. The new device is called multicycle integration focal plane array (MIFPA). MIFPA makes lock-in amplification and boxcar-gated integration, which work so far only for a single detector, feasible for array configuration. MIFPA has three modes of operation — lock-in (LI), gated (G), and gated lock-in (GLI) modes. The application of MIFPA is in the detection of extremely weak imaging, spectroscopic, and spectroscopic imaging.

### **2. Description of Prior Art**

In the past few decades, the lock-in amplifier and boxcar-gated integrator have played important roles in the detection of extremely weak signals buried in strong background noises. However, the lock-in amplifier and boxcar-gated integrator, being sophisticated electronics systems, work only for a single detector. For array detectors, either linear or area, for imaging, spectroscopic, and spectroscopic imaging applications, the staring focal plane arrays (FPA) were invented. In the existing FPA technology, each pixel has a semiconductor photodiode, the photocurrent (signal plus background) of which goes through single-cycle integration (SI). When signal is extremely weak in comparison with background, the signal to noise ratio, dynamic range, and other criteria of performance of the existing single-cycle integration focal plane array (SIFPA) are limited by its integration time. It cannot achieve the level of performance of the lock-in amplifier. By replacing the FPA's single-cycle integration (SI) with multi-cycle integration (MI), we turn SIFPA into MIFPA. MIFPA can operate in three modes — lock-in (LI), gated (G), and gated lock-in (GLI) modes. LI-MIFPA and G-MIFPA incorporate the

concepts of lock-in amplifier and gated integrator into the array configuration, respectively. LI-MIFPA can perform lock-in imaging, spectroscopy, and or spectroscopic imaging. G-MIFPA can perform gated imaging, spectroscopy, and or spectroscopic imaging. GLI-MIFPA has the features of both LI-MIFPA and G-MIFPA.

## **SUMMARY OF THE INVENTION**

A new type of focal plane array (FPA) — multi-cycle integration focal plane array (MIFPA) — has been invented for lock-in, gated, or gated lock-in detection of extremely weak image and/or spectroscopic signals buried in strong background. The principles, theory, circuit designs, computer simulation, fabrication, experimental results, and application methods of the MIFPA are disclosed. The total signal integration time of the MIFPA is several orders greater than the single-cycle integration focal plane array (SIFPA), which is the existing FPA technology. As a result, the sensitivity of weak signal detection, the dynamic range, and other criteria of performance of the MIFPA are several orders better than those of the SIFPA. In addition, the MIFPA also reduces significantly low-frequency noises. This essential feature of MIFPA is the reason why MIFPA is far better than the widely used method of multi-image (acquired by the existing SIFPA technology) averaging using image processing software, which inevitably includes the low frequency noise and other noises associated with the multiple utilization of the A/D converter of the data acquisition system. The MIFPA can operate in three modes — the lock-in (LI), gated (G), and gated lock-in (GLI) modes.

In LI-MIFPA, radiation from the scene or object, and therefore the signal photocurrent, is modulated either passively or actively, while dark and/or background currents are not. By using a correlated multi-cycle integrator, the signal current is accumulated while the dark or background current is cancelled. As a result, the total integration time for each pixel is increased by several orders, and so is the improvement of the imager's signal to noise ratio and dynamic range. In G-MIFPA, the direction of integration of the correlated multi-cycle integrator does not change as in the BC-MIPFA. The integrator is triggered on by the arrival of the pulse of signal photocurrent, and turned off after the pulse disappears. It remains inactive until its trigger by the arrival of the next pulse of signal photocurrent. The LI-mode is used for the detection of extremely weak constant signal. The G-mode is appropriate for periodically arrived (for example, a pulsed-laser excited fluorescence spectroscopy)

short photocurrent pulses. The GLI-mode is for periodical pulsed signal, which is buried under strong background, and therefore the principles of both LI-mode and G-mode are utilized.

MIFPA is a generic electronic device that can be used for imaging, spectroscopy, and/or spectroscopic imaging. It is valid for any source of signal electrical current, including photonic, electrical, magnetic, and thermal. The principles and circuit designs of MIFPA can be used as long as the signal is extremely weak and/or short in comparison to the background. It is not limited by the specific method of lock-in and/or gating, neither is it by the type of detectors.

## BRIEF DESCRIPTION OF THE SYMBOLS AND DRAWINGS

### 1. Definition of Symbols

- $I_s$  DC image signal photocurrent generated in the detector by the scene of imaging.  $I_s$  is defined as the average of the real image signal current  $i_s$ , which is time varying, through its integration cycle.
- $I_d$  DC dark current thermally generated.  $I_d$  is defined as the average of the time-varying real dark current  $i_d$ .
- $I_b$  DC background current, which is generated by photons of the same wavelengths under detection. As  $I_s$  and  $I_d$ ,  $I_b$  is defined as the average of the time varying real background current  $i_b$ . When  $I_b$  can be modulated separately from signal current  $I_s$ , the background current  $I_b$  plays the same role as the dark current  $I_d$ . In this invention, we treat  $I_b$  and  $I_d$  as equivalent, using  $I_b$  to denote both of them.
- $e$  charge of an electron,  $1.6 \times 10^{-19}$  C.
- $N_s$  number of integrated photoelectrons generated by a steady signal photon flux.
- $\overline{n_{ro}^2}$  noise due to readout electronics.

$\overline{n_{1/f}^2}$	1/f or low frequency noise mostly associated with the fabrication process of the photodetector.
$\overline{n_{th}^2}$	detector thermal noise.
$\overline{n_s^2}$	shot noises associated with the steady signal current.
$\overline{n_b^2}$	shot noises associated with the steady background current.
$\sqrt{\overline{n_b^2}}$	root mean square (rms) value of background current generated shot noise, which is the predominant noise source under the condition of $I_s \ll I_b$ .
$N_{sat}$	saturation or maximum number of electrons that an integration capacitor can handle.
$m$	number of integration cycles of the correlated multi-cycle integrator.
$\tau$	period of each cycle of integration for lock-in MIFPA.
$\tau_{on}$	gate-on or integration duration time for gated or gated lock-in MIFPA.
$\tau_{off}$	gate-off or non-integration duration time for gated or gated lock-in MIFPA.
$\alpha$	weigh of gate-on duration, defined as $\alpha = \frac{\tau_{on}}{\tau} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}}$
$T_i$	Total integration time.  For LI- MIFPA, $T_i = m \tau$ ;  For G-MIFPA and GLI-MIFPA, $T_i = m \alpha \tau = m \tau_{on}$ .
$R$	Signal to noise ratio, defined as $R = Signal / Noise = \frac{N_s}{\sqrt{\overline{n^2}}}$ , where $N_s$ is the number of electrons due to the signal current $I_s$ , and $\overline{n^2}$ is the root mean square value of the total number of electrons due to random noise.
$D$	Dynamic range in decibels, defined as $D = 20 \log_{10} R_{max}$ , when the maximum integration time is utilized.

- $f$  Frequency.
- $m$  number of integration cycles of MIFPA
- $\omega$  Angular frequency.  $\omega = 2\pi f$
- $\omega_m$  Modulation frequency.  $\omega_m = 2\pi f_m = 2\pi / \tau$ .
- $T(\omega)$  Noise transmission window of a conventional single cycle integrator for a conventional FPA
- $T(\omega) = \sqrt{V_o(\omega, \phi) V_o^*(\omega, \phi)}$ , where  $V_o(\omega, \phi)$  is the output voltage of the integrator with a unit harmonic current  $i(t) = e^{j(\omega t + \phi)}$  as the input.
- $T_m(\omega)$  Noise transmission window of a correlated multi-cycle integrator for a LI-MIFPA
- $T_{p-L}(\omega)$  Transmission window of typical phase sensitive detector plus low pass filter
- $T_{LI}(\omega)$  Transmission window of typical single detector lock-in amplifier
- $H_L(\omega)$  Transfer function of low pass filter
- $H_S(\omega)$  Transfer function of signal channel

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## **DETAILED DESCRIPTION OF THE INVENTION**

During the course of this description, like numbers will be used to identify like elements according to different figures which illustrate the invention.

### **1. Deficiencies of Existing FPA Technology for Detecting Extremely Weak Signals**

The lock-in (LI) amplifier and gated integrator (GI) have been playing important roles in the detection of weak photon signals. They were developed for a single photodetector. For the focal plane array (FPA) or image sensor, which utilizes a staring linear or area array of photodetectors to simultaneously detect an array of photon signals, the periodic integration of photocurrent is used to improve signal to noise ratio. The sensitivity of a semiconductor photodetector is characterized by its signal to noise (voltage or current) ratio  $R$

$$R = \text{Signal} / \text{Noise} = \frac{N_s}{\sqrt{\overline{n_{ro}^2} + \overline{n_{1/f}^2} + \overline{n_{th}^2} + \overline{n_s^2} + \overline{n_b^2}}} \quad (1)$$

where  $N_s$  is the number of integrated photoelectrons generated by a steady signal photon flux, and the denominator is the root mean square (rms) value of the total number of noise electrons. The noise electrons are from various sources.  $\overline{n_{ro}^2}$  is the noise due to readout electronics,  $\overline{n_{1/f}^2}$  the 1/f or low frequency noise mostly associated with the fabrication process of the photodetector,  $\overline{n_{th}^2}$  the detector thermal noise, and  $\overline{n_s^2}$  and  $\overline{n_b^2}$  the shot noises associated with the steady signal and background currents, respectively. Note that the DC background current  $I_b$  and dark current  $I_d$  have the same effect. We use  $I_b$  to represent the sum of  $I_b$  and  $I_d$ , and  $\overline{n_b^2}$  to represent the rms value of the number of noise electrons associated with  $I_b$  and  $I_d$ . When  $I_b$  (DC) is several orders greater than signal current  $I_s$  (DC), the shot noise  $\overline{n_b^2}$  may be predominant among all the components of the noise electrons. Therefore, Eq. (1) can be simplified as

$$R = \text{Signal} / \text{Noise} \approx \frac{N_s}{\sqrt{\overline{n_b^2}}} = \frac{N_s}{\sqrt{N_b}} = \frac{I_s}{\sqrt{eI_b}} \sqrt{T_i} \quad (2)$$

where  $N_b$  is the number of integrated electrons due to DC background and/or dark current  $I_d$ ,  $e$  the electron charge,  $T_i$  the signal integration time (approximately equal to the frame period for a staring FPA). Here we use the equation

$$\overline{n_b^2} = N_b = \frac{I_b T_i}{e} \quad (3)$$

which is valid for photovoltaic detectors. If the detectors are photoconductors, such as QWIP's, the rms value  $\sqrt{\overline{n_b^2}}$  of background current generated shot noise electrons as expressed by Eq. (3) will be multiplied by a factor of square root of 2. Other equations in the following discussion will be modified with a similar factor of correction, which does not affect substantially our conclusions of MIFPA.

Eq. (2) indicates that the signal to noise ratio is proportional to the square root of integration time  $T_i$  of each pixel. However,  $T$  is limited by  $N_{sat}$ , the saturation or maximum number of electrons that an integration capacitor can handle. Note that  $N_{sat}$  is limited by two factors. First, the capacitance

can only be in the range of pF due to real estate limit in the FPA; secondly, the increase of the capacitance will induce a higher kTC noise. All the existing FPA technologies use single-cycle integration (SI) of signal (note that in the case of gated intensified CCD imaging system the FPA still operates in SI mode). For the CMOS FPA, the capacitance trans-impedance amplifier (CTIA) is the most widely used readout interface. Thus

$$T_i = \frac{eN_{sat}}{I_s + I_b} \approx \frac{eN_{sat}}{I_b} \quad (4)$$

Using signal integration time defined by Eq. (3), we can obtain the optimized signal to noise ratio for the existing single-cycle integration focal plane array (SIFPA) technology using CTIA

$$R_{SIFPA,opt} = (Signal / Noise)_{SIFPA,max} \approx \frac{I_s}{I_b} \sqrt{N_{sat}} \quad (5)$$

Assuming  $R_{SIFPA,opt} = 1$ , we have the theoretical minimum detectable signal current to background current ratio for a SIFPA

$$(I_s / I_b)_{SIFPA,min} \approx \frac{1}{\sqrt{N_{sat}}} = 1.63 \times 10^{-4} \quad (6)$$

where we assume that the integrator has a storage capacitor with capacitance of 2 pF and saturation voltage of 3V. Apparently, the existing FPA technology of single-cycle integration (SI) is inadequate to deal with many cases, in which the signal photocurrent to background current ratio  $I_s / I_b$  is extremely low, such as visible and infrared (IR) solar magnetography ( $< 10^{-4}$ ), liquid nitrogen temperature imaging using long wave length infrared (LWIR, 8 - 12  $\mu$ ) quantum well infrared photodetector (QWIP) array, 15  $\mu$  very long wavelength (VLWIR) imaging in space ( $10^{-6} \sim 10^{-5}$ ), Raman spectroscopy with near infrared (NIR) excitation, and VLWIR spectroscopic imaging of biomedical specimens ( $< 10^{-6}$ ).

## **2. Principles of Multicycle Integration Focal Plane Array (MIFPA)**

For extremely weak signal detection, by replacing single-cycle integration (SI) with multicycle integration (MI), we can increase the integration time by several orders, and therefore dramatically



improve the performance of the FPA, including (but not limited to) sensitivity and dynamic range. The multicycle integration focal plane array (MIFPA) can operate in lock-in (LI), gated (G), and gated lock-in (GLI) modes.

### **2.1. Lock-In Multi-cycle Integration Focal Plane Array (LI-MIFPA)**

To elicit the principles of MIFPA, we use its basic operation mode – lock-in focal plane array (LI-MIFPA) for extremely weak signal imaging, the critical component of which is a correlated multicycle integrator (CMI, also called CMI unit-preamplifier) 31 for each pixel, as shown in Fig. 1 and 2. LI-MIFPA's application for spectroscopy and spectroscopic imaging is an obvious extension of its application for imaging. The other two modes of operation – G-MIFPA and GLI-MIFPA – are similar to LI-MIFPA. The only difference is that the CMI of the G-MIFPA and GLI-MIFPA is programmed to shut off during the period of time when there is no signal, and the CMI of the LI-MIFPA keeps functioning.

The CMI accumulates the signal while canceling the background. The schematic shown in Fig. 1 and 2(a) is for the simplest and most common case – imaging using passive modulation. A lens or lens system 12 is placed between the object or scene 10 and the focal plane array 13, composed of either one- or two-dimensional of photodetectors 16, where the image is formed. A passive optical modulator 11, which can be a mechanic chopper, an electric-optical switch, a polarizer, or other devices, is placed between the object 10 and the FPA 13 to modulate the photon flux from the scene or object for imaging, spectrum, or spectroscopic imaging. The signal can also be actively modulated by a pulsed light source 15 (Fig. 2 (b)), in which the signal photon flux is generated by modulated power source, such as a pulse laser. When the modulator is on in one phase ( $\phi_1$  in the figure), the current generated by the detector will be the signal photocurrent  $I_s$  from object 10, plus the DC background current  $I_b$  from the radiation 14 not modulated. When the radiation from the imaging target is blocked by the modulator in another phase  $\phi_2$  of equal duration as  $\phi_1$ , only the DC  $I_b$  is present. By controlling the correlated multicycle integrator synchronically with the modulation control signal, the integrator charges the capacitor with the signal and background currents in  $\phi_1$ , but discharges it with background current only in  $\phi_2$ . Discharged by the background current in each cycle, the capacitor is saved for signal current integration, and the total integration time is increased.

The photocurrent 17 or  $I_{in}$  ( $I_{in} = I_s + I_b$ ) generated by each photodetector 16, which is composed of the modulated  $I_s$  from object 10 and the DC current  $I_b$  from the unmodulated radiation 14 or dark

current, is fed to either 18 or 19 of the demodulator 29, controlled by the correlated controller 28. 28 is a square wave generator, which controls both the modulator 10 or 15 and the demodulator 29. The output of 29, which is  $I_s + I_b$  during phase  $\phi_1$  and  $-I_b$  during phase  $\phi_2$ , is fed to an integrator 30, the most commonly used version of which is the capacitance transimpedance amplifier (CTIA). The demodulator and the integrator are the two critical components of the conventional lock-in amplifier. The demodulator and the integrator are combined in MIFPA and called correlated multicycle integrator (CMI) 31.

The advantages of LI-MIFPA over SIFPA are:

### **2.1.1. Advantages of Lock-In Multi-cycle Integration Focal Plane Array (LI-MIFPA)**

#### **(a) Improvement of Signal to Noise Ratio**

In LI-MIFPA, Eq. (4) is replaced by

$$T \approx \frac{eN_{sat}}{I_s} \quad (7)$$

Using signal integration time defined by (6), we can obtain the optimized signal to noise ratio for MIFPA

$$R_{MIFPA,opt} = (Signal / Noise)_{MIFPA,max} \approx \sqrt{\frac{I_s}{2I_b}} \sqrt{N_{sat}} \quad (8)$$

The improvement of signal to noise ratio is a factor of

$$\sqrt{\frac{I_b}{2I_s}} \quad (9)$$

Assuming  $R_{MIFPA,opt} = 1$  in (7), for the same integration capacitance and saturation voltage, we have BC-MIFPA's theoretical minimum detectable signal to background ratio

$$\left(\frac{I_s}{I_b}\right)_{MIFPA,min} \approx \frac{2}{N_{sat}} = 5.04 \times 10^{-8} \quad (10)$$

A comparison of (10) and (6) shows that the BC-MIFPA improves the weakest detectable signal, as well as signal to noise ratio, by more than three orders.

### **(b) Improvement of Dynamic Range**

In addition to signal to noise ratio and weakest detectable signal, another important figure of merit of a focal plane array is its dynamic range. In terms of decibels, the dynamic range  $D$  of a conventional SIFPA is

$$D_{SIFPA} = 20\log_{10} R_{SIFPA, \max} = 20\log_{10} \left( \frac{I_s}{I_b} \sqrt{N_{sat}} \right) \quad (11)$$

whereas for a MIFPA it is

$$D_{MIFPA} = 20\log_{10} \left( \sqrt{\frac{I_s N_{sat}}{I_b}} \right) \quad (12)$$

The improvement of dynamic range is

$$D_{MIFPA} - D_{SIFPA} = 20\log_{10} \left( \sqrt{\frac{I_b}{I_s}} \right) \quad (13)$$

If  $I_b / I_s > 10^4$  as in the case of solar magnetography, improvement of dynamic range will be more than 37 dB.

### **(c) Suppression of Low Frequency Noise**

As shown in Fig. 1, in the method of BC-MIFPA both the signal and background are fed to the correlated multicycle integrator. The noise current generated in the detector also goes through the correlated multicycle integrator. The noise transmission window of the correlated multicycle integrator is

$$T_m(\omega) = \sqrt{V_o(\omega, \phi) V_o^*(\omega, \phi)} = \frac{T}{C} \left| \frac{\tan\left(\frac{\omega T}{4m}\right) \sin\left(\frac{\omega T}{2}\right)}{\frac{\omega T}{2}} \right| \quad (14)$$

where  $T$  is the total integration time,  $m$  the modulation frequency, and  $C$  the charge storage capacitor. For comparison, also shown in Fig. 2 is the noise transmission window (15) of a single-cycle integrator used in a conventional SIFPA

$$T(\omega) = \sqrt{V_o(\omega, \phi) V_o^*(\omega, \phi)} = \frac{\left| 2 \sin\left(\frac{\omega T}{2}\right) \right|}{\omega C} \quad (15)$$

In both cases, the rms value of the total number of noise electrons is the same

$$\sqrt{n_b^2} = \sqrt{V_n^2} \frac{C}{e} = \frac{C}{e} \left[ \int_0^\infty T^2(\omega) w(f) df \right]^{1/2} = \sqrt{I_b T / e} = \sqrt{N_b} \quad (16)$$

for the same total integration time. Comparing the two spectra of Fig. 2, however, we note that the transmission function  $T(\omega)$  of a single-cycle integrator is that of a low pass filter with bandwidth equal to  $1/2T$ , while the transmission function of the correlated multicycle integrator is that of a band pass filter peaked at the modulation frequency  $\omega_m$ , with satellite windows centered at the odd harmonics of  $\omega_m$ . An apparent advantage of LI-MIFPA then lies in its capability of suppressing the flicker or  $1/f$  noise, which, among all the noise sources, is usually important, and even dominant for some types of widely used detectors, such as InGaAs, InSb, and HgCdTe IR photodetectors.

#### **(d) On-Chip Data Processing**

In current FPA technology, multi-image (up to 10,000 images in solar magnetography) averaging with image processing software is utilized to extract extremely weak signal buried in strong background. Even with the help of dithering, this averaging method is limited and unreliable. In contrast, BC-MIFPA performs various functions of on-chip data processing, including addition, subtraction, averaging, and direct extraction of useful signals. As a recent trend in the development of FPA, direct on-chip data processing is preferred because of its efficiency. We can effectively avoid the system limitations imposed by the slow speed and statistical errors imposed by the high precision analog to digital converter. In addition, SIFPA's multi-image averaging will inevitably include the  $1/f$  noise, which is eliminated by MIFPA.

#### **2.1.2. Comparison of Lock-in MIFPA and Conventional Lock-in Amplifier**

The block diagram of a basic lock-in amplifier is shown in Fig. 3. The key components are the phase sensitive detector (PSD), which demodulates the modulated signal to recover the signal as DC or low frequency components, and the low pass filter (LPF), which reduces the bandwidth of the noise (the signal as well), recovering weak signals buried in strong noise. In frequent domain  $\varpi$ , a unit harmonic input fed to the PSD leads to an output from the LPF

$$V_{out}(\varpi; \omega, \phi) = \frac{2}{\pi j} e^{j\phi} \sum_{k=-\infty}^{\infty} \frac{1}{2k+1} \delta[\varpi - (2k+1)\omega_m - \omega] H_L(\varpi) \quad (17)$$

where  $\omega$  and  $\phi$  are the frequency and phase of the input, respectively, and  $H_L$  is the transfer function of the LPF. Note that the output  $V_{out}$ , which depends on the input  $\omega$  and  $\phi$ , is expressed in the frequency domain  $\varpi$ . Since the LPF of most lock-in amplifiers has a very narrow bandwidth, the output only has DC and low frequency terms. Neglecting cross talk terms  $H_L[\omega + (2k+1)\omega_m] \times H_L[\omega + (2k'+1)\omega_m]$ , and following (14), we can calculate the transmission window of the PSD+LPF as a function of the input frequency

$$T_{P-L}(\omega) = \sum_{k=0}^{\infty} \frac{2}{(2k+1)\pi} |H_L[\omega - (2k+1)\omega_m]| \quad (18)$$

In addition to PSD + LPF, the typical lock-in amplifier has a pre-amplifier and a band pass filter in its signal channel. The pre-amplifier brings the small signal to a level sufficient to overcome the noise induced by the PSD, which is a switch that generates noises at various frequencies. The band-pass filter rejects unnecessary interference and noise by filtering out the satellite peaks of (19). Therefore the transmission window of the lock-in amplifier is a single peak centered at the modulation frequency, with its bandwidth defined by the LPF

$$T_{LI}(\omega) = \frac{2}{\pi} |H_L(\omega - \omega_m)| \times |H_S(\omega)| \quad (19)$$

where  $H_S(\omega)$  is the transfer function of the signal channel. For comparison, (18), (19), and (14) are plotted in Fig. 4. Note that in Fig. 2, we plot (14) from 0 to the range of  $\omega_m$ , while in Fig. 4, we plot (14) for the whole wide range of spectrum, revealing its double satellite structure.

The critical component of LI-MIFPA is correlated multicycle integrator, which is a combination of phase sensitive detector and integrator. Since the integrator is a special type of low pass filter, LI-

MIFPA is a special version of PSD+LPF. As shown in Fig. 4, (18) of the PSD+LPF of a typical lock in amplifier, which uses a second order RC low pass filter, and (14) of the LI-MIFPA have the similar feature of satellite peaks. The difference of (18) and (14) is in the sub-satellite peaks of the LI-MIFPA. Unlike the second order RC low pass filter, the transfer function of the integrator in LI-MIFPA has satellite peaks.

## **2.2. Gated Multicycle Integration Focal Plane Array (G-MIFPA)**

MIFPA can also operate in gated (G) mode when signals appear in short pulses. In each cycle of integration with period  $\tau$  the on-time of the integrator is much shorter than the off-time ( $\alpha \ll 1$ , Fig. 5). The G-MIFPA can operate without (Fig. 5.a) or with (Fig. 5.b) background cancellation. The device operates as the gated lock-in multicycle focal plane array (GLI-MIFPA) when it is programmed to perform background subtraction.

### **2.2.1. Simple Gated Multicycle Integration Focal Plane Array (G-MIFPA)**

G-MIFPA is used when the number of integrated signal electrons is many orders smaller than that of the background and/or dark current electrons ( $\alpha I_s \ll I_b$ , but  $\alpha I_s$  is not  $\ll I_b$ , as in the case of IR fluorescence spectroscopy using nano-second pulse laser excitation). In G-MIFPA the direction of integration of the correlated multicycle integrator does not change as in the LI-MIPFA. The integrator is turned on by a trigger signal from the gate control circuit to integrate the signal photocurrent pulse, and turned off after a certain increment of time. It remains inactive until it is triggered again for the next signal pulse (Fig. 5.a). By keeping the integrator off we can avoid the shot noise when there is no signal.

### **2.2.2. Gated Lock-in Multicycle Integration Focal Plane Array (GLI-MIFPA)**

If the signal is not only short, but is also associated with a much stronger background (in comparison with the background during the signal-off time, as in the case of LWIR spectroscopy using nano-second pulse laser excitation),

$$\alpha \ll 1 \quad (20)$$

$$I_s \ll I_b \quad (21)$$

then GLI-MIFPA can be used. In GLI-MIFPA, the correlated multicycle integrator of the GLIMIFPA goes through three phases (Fig. 5.b). In  $\phi_1$ , which lasts  $\alpha\tau$ , the integrator integrates both the signal pulse and strong background currents. In  $\phi_2$ , which has the same duration as  $\phi_1$ , the integrator reverses its direction of integration, and cancels the background of  $\phi_1$ . In  $\phi_3$ , which lasts much longer than  $\phi_1$  or  $\phi_2$ , the integrator is turned off. The GLI-MIFPA combines the advantage of the G-mode — reduction of the on-time of the integrator to increase the integration time — and that of the LI mode — cancellation of background to increase the integration time.

### **3. Feasibility of MIFPA**

#### **3.1. MIFPA Circuit Design**

The only difference of the conventional SIFPA and MIFPA is their integrator. The success of lock-in imaging using MIFPA depends on the circuit design of its correlated multicycle integrator, which must have as few devices as possible so that it can be incorporated into the array format. Fig. 6 is one of the circuitry designed for MIFPA, which comprises two stages. The second stage S2 is integrator **30** (the same numbering as in Fig. 1 and 2), the capacitive transimpedance amplifier (CTIA) widely used in the readout circuit of infrared (IR) FPA's. In this stage, **24** (the same as in Fig. 1) or feedback capacitor  $C$  of operational amplifier **26** (the same as in Fig. 1) is the main integrator, which accumulates signal throughout multi-cycle integration. **42** is the reset switch M5 enabled at beginning of integration with a narrow pulse, and reset after readout of the integrated signal. The first stage S1 is a special demodulator **29** (the same numbering as in Fig. 1 and 2). In this stage, **35** or capacitor  $C_i$  is a temporal integrator. M1, M2, M3, and M4 are the four MOSFET switches or gates of integrator **35**. M1 is kept on during the cycle of integration and needed for any FPA integrator. Only M2, M3, and M4 play the function of correlated switches of the demodulator **29**. The function of **29** is to integrate **17** (the same numbering as Fig. 1), or the input current  $I_{in}$  ( $I_s + I_d$ ) and to transfer the accumulated charges across **35a** and **35b** to **24a** and **24b** of  $C$  with opposite polarities depending on the gate

timings. When M2 and M3 are off and M4 is on during  $\phi 2$  (Fig. 1 and 2),  $I_{in}$  is integrated on  $C_I$  first. At the end of this half period of integration, by turning off M4 followed by turning on M2 and M3, the charges stored on **35b**, the right plate of  $C_I$ , is transferred to **24a**, the left plate of  $C$ . At the same time,  $C_I$  is reset. Assuming that the charges stored on **35b** are  $Q_1$ , the change of output voltage  $V_{out}$  at node **27** or **24b** after the transfer is  $\Delta V_{o1} = -Q_1/C$ . At the next phase or half period of integration, with M3 and M4 off and M2 on ( $\phi 1$  in Fig. 1), input current  $I_{in}$  (**15**) charges  $C_I$  and  $C$ . Assuming at the end of this period of integration the charges accumulated on **35b** or the right plate of  $C_I$  is  $Q_2$ , the change of output voltage  $V_{out}$  at node **27** after the transfer is  $\Delta V_{o2} = Q_2/C$ . By modulating the signal current  $I_s$  and not modulating the background and/or dark current  $I_d$ , we have  $Q_1 = Q_d$  and  $Q_2 = Q_d + Q_s$ , where  $Q_s$  is the integrated charge due to signal current  $I_s$ , and  $Q_d$  the integrated charge due to background and/or dark current  $I_b$ . Therefore, the total change of output voltage  $V_o$  at node **41b** or **27** after the two consecutive integrations is  $\Delta V_o = Q_s/C$ . Note that for some type of signal modulation  $\Delta V_o = 2 Q_s/C$ . The function of the CMI method — integration of signal and cancellation of background — is thus fulfilled. The time sequence of the gate control voltages  $V_1, V_2, V_3, V_4$ , and  $V_R$  control the switches  $M1, M2, M3, M4$ , and  $M5$ , respectively, as described above. The substrate of the five FET switches  $M1, M2, M3, M4$ , and  $M5$  are all grounded, which is not shown in Fig. 6.

### **3.2. MIFPA Circuit Simulation**

Fig. 7 is a computer simulation result of the Correlated Multicycle Integrator as shown in Fig. 6, by using the circuit simulation package HSPICE. 25 cycles of integration, with a total integration time of 5 ms, are shown in the figure. With the level of background current as shown in Fig. 7, the maximum integration time will be less than 0.5 ms if a single cycle integrator is used.

### **3.3. MIFPA Circuit Fabrication**

Fig. 8 is part of the layout of VLSI design of the silicon CMOS IC, which has various MIFPA circuitries, including single pixels, and linear and area arrays with multiplexers, as well as device parameter test fixtures. The figure shows one pixel of MIFPA, including both Versions I and III of the



correlated multicycle integrator. The chip was designed using HP's 0.5  $\mu$  CMOS design rules, and fabricated at HP's 0.5  $\mu$  CMOS facility, which was managed by MOSIS.

#### **4. Experimental Results of MIFPA**

Three categories of experimental testing were performed on the MIFPA chip. Fig. 9 is a photocopy of the graph taken from the screen of a tracer, which is used to test the design of the correlated multicycle integrator (CMI) as shown in Fig. 6. The Pulse Instrument Focal Plane Array Test Equipment setup is used to control the input and output of the Integrator. The modulation and correlated integration frequency of 31.25 kHz is generated by a pulse generator. With 30 cycles, a total time of 960  $\mu$ s is used for integration. The data of test results were fed to a tracer. The output of the integrator has exactly the same features as the simulation results shown in Fig. 7. It is therefore demonstrated experimentally that the Correlated Multi-Cycle Integrator functions as designed.

To test MIFPA's sensitivity, signal to noise ratio, and dynamic range, a near infrared (NIR) light emitting diode (LED) powered by a DC source was used to generate the background photocurrent  $I_b$   $1.5 \times 10^{-8}$  A, which was equivalent to a constant dark current  $I_d$  of the same magnitude in the NIR photodetector. A second NIR LED of the exact same characteristics, which was connected to a programmable square wave power supply with the same peak voltage as the DC power source of the first NIR LED. The second NIR LED generated modulated signal photocurrent  $I_s$  in the NIR photodetector. By adjusting the positions of the two LED's with respect to the photodetector, we can control the ratio of  $I_s/I_b$ . Fig. 10 shows the MIFPA output voltage  $V_o$  of the NIR photodiode as a function of the input  $I_s/I_b$ . The weakest signal measured in the experiment was  $(I_s/I_b)_{CMI,Measured} = 7 \times 10^{-5}$ . Note that the measured output error bar due to random fluctuation is 23 mV, the predominant source of which is the shot noise of the photodetector. By extending the straight line, or the output

voltage  $V_o$  as a function of the input  $I_s / I_b$ , as shown in Fig. 10, we conclude that the weakest detectable signal  $I_s / I_b$  in our experiment is

$$(I_s / I_b)_{min, CML, Experimental} \sim 1.4 \times 10^{-5} \quad (22)$$

A comparison of (23) and (6) shows that under the same background, the weakest measurable signal using our testing MIFPA chip is more than one order smaller than the theoretical limit of the measurable signal using the conventional FPA of single-cycle integration. Since other widely used figures of merit of the FPA, such as signal to noise ratio, dynamic range, and non-uniformity caused fixed pattern noise, are related to each pixel's weakest detectable signal, therefore we conclude that we have experimentally demonstrated the feasibility of MIFPA technology. Note that the theoretical limit of Eq. (9) was not achieved, since we used only 2,000 cycles of integration and a small portion of the available saturation output voltage of 3 V to avoid saturation. Saturation could be caused by feed through of capacitors, slow drifting of CMOS device parameters, and other instabilities of the electronics involved. With improvement of stability and uniformity of our devices and electronics, we can use longer integration time for each cycle, as well as more cycles of integration. As a result, a longer total integration time that is close to the theoretical limit can be implemented. We expect that the theoretical limit of the weakest detectable signal as depicted by Equation (10) will be approached with the maturity of MIFPA technology.

Fig. 11 (a) is the image of an object, which is taken by a single pixel of our first working MIFPA test chip, instead of the array, to avoid pixel nonuniformity induced noise. It is a letter T composed of 80 bright squares out of a total of 144 squares. While the dark squares do not generate any photocurrent, each of the bright squares generates a signal photocurrent of  $1.05 \times 10^{-12}$  A in the photodetector, which is equal to  $7 \times 10^{-5}$  of the background photocurrent  $1.5 \times 10^{-8}$  A. Fig. 11 (b) is the "image," or rather no image, of the same target under the same background ( $I_s = 1.05 \times 10^{-12}$  A,

unmodulated; and  $I_b = 1.05 \times 10^{-8}$  A) taken by the conventional imaging method of single-cycle integration. A comparison of Fig. 11 (a) and (b) clearly demonstrates the dramatic improvement MIFPA brings to the FPA technology of imaging and spectroscopy. Interestingly, we tried to “average” numerous figures (b) to obtain an image similar to (a). This widely used multi-image averaging method failed in our test.